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Hurricane Forecasting with the high-resolution NASA finite-volume General Circulation Model

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A high-resolution finite-volume General Circulation Model (fvGCM), resulting from a development effort of more than ten years, is now being run operationally at the NASA Goddard Space Flight Center and Ames Research Center. The model is based on a finite-volume dynamical core with terrain-following Lagrangian control-volume discretization and performs efficiently on massive parallel architectures. The computational efficiency allows simulations at a resolution of a quarter of a degree, which is double the resolution currently adopted by most global models in operational weather centers. Such fine global resolution brings us closer to overcoming a fundamental barrier in global atmospheric modeling for both weather and climate, because tropical cyclones and even tropical convective clusters can be more realistically represented. In this work, preliminary results of the fvGCM are shown. Fifteen simulations of four Atlantic tropical cyclones in 2002 and 2004 are chosen because of strong and varied difficulties presented to numerical weather forecasting. It is shown that the fvGCM, run at the resolution of a quarter of a degree, can produce very good forecasts of these tropical systems, adequately resolving problems like erratic track, abrupt recurvature, intense extratropical transition, multiple landfall and reintensification, and interaction among vortices.

1. Introduction

Numerical forecasting of tropical cyclones presents several difficulties for general circulation models (GCMs), the most important being the resolution. The horizontal resolution adopted by current operational GCMs is generally not sufficient to adequately resolve the tropical cyclone's structure and tropical weather systems in general. In particular, tropical cyclones in General Circulation Models generally appear as broad and weak vortices

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in which the vertical structure resembles that observed only to a first approximation. To increase the resolution of GCMs for operational use is not trivial, because it involves many aspects ranging from purely theoretical to computational. Since operational weather forecasts need to be released in real time, the resolution currently adopted by many operational centers around the world, of the order of 0.5° , represents a compromise between the contrasting needs of minimum possible computing resources and maximum possible resolution. This resolution is not suitable to resolve tropical cyclones, particularly with respect to their intensity and vertical structure. Therefore, global numerical weather forecasting in the Tropics still remains problematic.

For climate modeling, GCMs are being run at even lower resolution, often of 2.5° or coarser, because of the need for very long runs (years or even centuries). At these resolutions, the signatures of tropical cyclones, when present, are even broader and weaker and, even if the large-scale heat and moisture transport can be very realistic, the poor representation of the tropical cyclone is a serious problem. In fact, tropical cyclones locally represent a prominent fraction of the annual precipitation and globally a major source of interannual variability. Therefore, to perform long climate model simulations without the ability of generating realistic tropical cyclones undermines confidence in the estimate of interannual variability of precipitation in tropical and subtropical regions.

Finally, an increased interest in 'extreme events', particularly with respect to their fluctuations and statistical properties in various possible future climate scenarios, makes it imperative to be able to address the question of if and how the intensity and frequency of tropical cyclones would change, if climate changed. This question cannot be rigorously answered with the current resolution of global climate models.

In this article we show that some of these limitations are overcome with the new finite-volume General Circulation Model (fvGCM) developed at the NASA Goddard Space Flight Center (GSFC), and currently being run at a resolution of quarter of a degree. The global resolution of 0.25° brings a fundamental improvement in the way in which the tropical atmosphere in general, and hurricanes in particular, are being represented and predicted. One prominent aspect of the high resolution NASA fvGCM, developed as a part of the ALTIX project, is the very strong emphasis put on its highly efficient dynamical core design (Lin, 2004) and parallel implementation (Putman et al., 2004) that performs efficiently on a variety of parallel architectures (Lin et al., 2004).

In this work we present some of the results obtained with this model in simulating four tropical systems that developed in September 2002 and August 2004.

2. The Model

The fvGCM is based on the finite-volume dynamical core with terrain-following Lagrangian control-volume discretization documented in Lin (2004). The development of the finite-volume dynamical core at NASA GSFC is the result of more than ten years of intense effort, in which the most fundamental steps are: 1) development of algorithms for transport processes of water vapor (Lin et al., 1994); 2) development of multi-dimensional "Flux-Form Semi-Lagrangian Transport" scheme (FFSL, Lin and Rood, 1996); 3) adaptation of the FFSL algorithm to the shallow water dynamical framework (Lin and Rood,

1997); 4) development of a simple finite-volume integration method for computing pressure gradient in general terrain-following coordinates (Lin, 1997).

Another crucial aspect of the fvGCM development is its high computational efficiency, possible thanks to a careful design aimed to optimize performance on a variety of computational platforms including distributed memory, shared memory and hybrid architectures (Putman et al., 2004). The new fvGCM is currently being run on one 512-CPU SGI-Altix system, which is one node of a supercomputer named Columbia, operational at the NASA Ames Research Center (ARC). The Altix nodes use Intel Itanium-II 1.5GHz processors, and are running ProPack Linux operating systems. At a resolution of 0.25° , with 32 vertical levels, which is the one adopted for this work, it takes only about 3700 seconds to finish a 5-day forecast by using 240 CPUs. Software engineers at ARC NAS (NASA Advanced Simulation Division) and GSFC NCCS (NASA Center Computing Simulation) are currently trying to further optimize the fvGCM codes for an even better throughput.

In this work we present the results of 15 simulations involving four hurricanes: Gustav and Isidore (2002) and Bonnie and Charley (2004). The global initial conditions (ICs) for the dynamic fields for all the experiments are provided by the National Centers for Environmental Predictions (NCEP). These are interpolated horizontally and vertically (Lin, 2004) but no additional data assimilation or bogusing of any kind is performed.

3. The Experiments

3.1. The Atlantic Tropical Systems of September 2002

The 2002 Atlantic hurricane season produced four hurricanes, all in September (Pasch et al., 2004). In this work we focus on hurricanes Gustav (8-12 September) and Isidore (14-27). These two systems are interesting because of the difficulties they present to numerical models, due to their complex tracks and dynamical evolution.

Gustav was a category 2 hurricane, that started as a subtropical depression at 1200 UTC 8 September (Pasch et al., 2004). The system moved erratically west-northwestward on 9 September and slowly strengthened. It then underwent a rapid tropical development becoming a tropical storm at 1200 UTC 10 September, skirting the North Carolina coast at about 2100 UTC, and then abruptly recurving northeastward (Beven, 2002). Although its intensity is not remarkable, it is worth noting that the system intensified under the influence of a mid-latitude system over New England, and underwent a very intense extratropical transition becoming a strong baroclinic system (center pressure at about 970 hPa) by 0000 UTC 13 September.

Isidore was a slow-moving and relatively long-lived tropical cyclone with a fairly complex track. It became Tropical Storm Isidore at 0600 UTC 18 September, Hurricane at 1800 UTC 19 September (Avila, 2003), hit northwestern Cuba, then recurved southward hitting the Yucatan peninsula as a category 3 hurricane. After landfall, the system lingered for more than 24 hours over northern Yucatan and then it returned to the ocean tracking northward, and eventually reaching Louisiana at 0600 UTC 26 September as a strong tropical storm (Pasch et al., 2004).

3.2. Simulation of Hurricane Gustav

In Fig. 1 the official observed 'best track' of hurricane Gustav is displayed, as provided by the National Hurricane Center (NHC). The system moves erratically in the first hours, then deepens, recurves and accelerates during an intense extratropical transition. During its recurvature, the cyclone skirts the North Carolina coast, affecting it within the radius of maximum wind (Beven, 2002). On the same panel, the fvGCM forecast initialized at 0000 UTC 8 and 9 September are shown. In the first simulation, Gustav was not defined, even as an extratropical low, so it is absent from the initial conditions. In spite of this severe limitation, the fvGCM develops a tropical cyclone-like vortex which approaches the North Carolina coastal line but then recurves to the ocean, as in the observations. The 48 hour forecast is very good, and the 72 hour forecast position differs from the observed one by only about 150 km. This is a remarkably small error considering the complexity of the recurvature. The subsequent run, initialized at 0000 UTC 9 September, is characterized by an even smaller error in the first 48 hours. This is due to a slightly better defined vortex in the ICs. The simulation also represents very well the acceleration associated with the extratropical transition, and the displacement error at 72 hour is of the order of only 250 km. This is also a very small error, since 72-hour displacement errors of storms produced by extratropical transitions are generally much larger, of the order of 500 km or more.

However, the most remarkable feature of the high resolution fvGCM is the representation of the storm's intensity at two different stages, both important phases of Gustav's life-cycle: the proximity to North Carolina around the recurving time, and the completion of its merging with an extratropical system, which creates a powerful 970 hPa low. For most models, to capture a tropical cyclone intensity, reproduce the extratropical transition, the merging of an extratropical remnant with a baroclinic storm, and later further deepening and intensification, generally presents major difficulties. In Fig. 2a,b, the sea level pressure is shown, relative to the initialization of the two runs, at 0000 UTC 8 and 9 September. The storm is not defined in the first simulation, and is slightly better defined in the second simulation. The observed center pressure at 0000 UTC 9 September was 1004 hPa (Beven 2002) whereas in the ICs the center's minimum is about 1007 hPa. In the central panels two forecasts issued from both initial conditions are shown. Fig. 2c shows the 72-hour forecast for 0000 UTC 11 September (initialized at 0000 8 September). The model produces a small-scale low with about 999 hPa of center pressure, very accurately placed. For verification, see the panel below (Fig. 1e), which shows the corresponding NCEP analyses for the same time (0000 UTC 11 September).

Fig. 2d shows the 84-hour forecast for 1200 UTC 12 September, initialized at 0000 UTC 9 September and in Fig. 2f the corresponding NCEP validating analyses are plotted. It can be noted that the fvGCM, starting from the weak vortex in Fig.2b, was capable of producing a remarkable extra-tropical transition and generate a baroclinic low very close to New Foundland, in agreement with observations. The cold front associated with the newly developed low, visible in both analyses (Fig. 2f) and satellite imagery (not shown), is sharply defined in the fvGCM forecast (Fig. 2d), indicating that the fvGCM has captured the extratropical transition very well.

3.3. Simulation of Hurricane Isidore

In Fig.3 the NHC observed best track and the tracks obtained from 7 simulations of hurricane Isidore are shown. The important aspects of Isidore's track are: 1) the erratic behavior during the first two days; 2) the landfall over western Cuba on the 21st; 3) the landfall over Yucatan on the 23th; 4) stationarity over the Yucatan for more than a day; 5) the abrupt northward turn and return over water with final landfall over Louisiana (Avila, 2002).

The first two runs, initialized on 18 and 19 September, capture the landfall over Cuba in their 48- and 72-hour forecast very well. Eventually, the model makes an attempt to force the cyclone recurving southward in the 4-5 day forecast. However, much more strongly than in the case of Gustav, the model is penalized in these two first simulations by a very poor definition of Isidore in the ICs, lacking even a closed circulation (not shown). The subsequent simulations have better defined signatures of the vortex in the ICs (although still far from optimal). In particular, the simulation initialized at 0000 UTC 20 September, encompasses in the 120-hour integration period all the relevant events of Isidore's life-cycle and produces a remarkably good track throughout the entire simulation: 1) landfall over western Cuba, 2) southward recirculation and 3) second landfall over the Yucatan.

The intensification in the fvGCM is also remarkable. The maximum observed intensity occurs at 1200 UTC 22 September when Isidore's center pressure is 934 hPa (Avila 2002). The fvGCM initialized on September 20th, starts from a broad vortex, as defined in the global ICs, of approximately 998 hPa (not shown). The actual observed value for that time is 979 hPa (Avila 2002), almost twenty hPa lower. However, in spite of this limitation, the dynamical core of the fvGCM can produce a minimum of approximately 960 hPa in the 60-hour forecast for 1200 UTC 22 September. In Fig. 4a the slp pressure for 1200 UTC 22 September is shown, and the 1° NCEP analyses are shown for comparison. The analyses are not able to represent the true intensity but provide an indication of Isidore's position.

The observed and simulated change in intensity between 0000 UTC 20 September and 1200 UTC 22 September are both of the order of 40 hPa, but the fvGCM starts from a value which is about 20 hPa higher than the observed. It can therefore be speculated that the fvGCM, with a better-defined vortex in the initial conditions, could produce even more realistically deep tropical cyclones.

In Fig. 4c,d, the zonal and meridional vertical cross-sections of wind speed, relative vorticity and temperature, are shown, relative to the 60-hour forecast for the same time (1200 UTC 22 September). All the prominent features of observed hurricanes can be seen: a vertical column of low speed, a prominent warm-core, an intense gradient of cyclonic vorticity away from the eye. It has been observed that analyses at about 1° or less also do produce some of these features (e.g. Hou et al., 2004); however, the scale of the system is substantially larger. In fact, in lower resolution GCMs the tropical cyclone-like vortex encompasses a much larger scale: typically the radius of maximum wind is of the order of 2-300 km, whereas in our case it is of less than 100 km. Other prominent features of tropical cyclones that are represented well in the fvGCM, but not in current GCMs, are: 1) the presence of anticyclonic vorticity in the higher levels, 2) the maximum wind in the lowest levels (generally

in the GCMs the maxima are at an excessive altitude) and 3) the intensity of the vorticity, which is of the order of $10^{-3} s^{-1}$ in our case, approximately one order of magnitude larger than the values observed in tropical cyclones as represented in GCMs.

3.4. Tropical Storm Bonnie and Hurricane Charley (2004)

Bonnie was first spotted as a tropical depression on 3 August 2004, but after a slow and discontinuous development, apparently dissipated. It regained organization and was named as a tropical storm on 10 August, making landfall on the Florida panhandle on August 12th. Charley was a category 3 hurricane that was first seen as a tropical depression on 9 August, and went through a rapid development becoming a tropical storm on the 10th and a hurricane on the 11th. It eventually made landfall over southwestern Florida. It is likely that because of their proximity, the large-scale flows associated with these two systems interacted strongly, which could be one of the reasons why the forecast of their track was somewhat more problematic than usual.

In Figure 5, the NHC tracks and our simulations are shown in the same frame. In the earliest simulation (initialized at 0000 UTC 11 August 2004) the fvGCM is again penalized by the complete absence of any vortex in correspondence to Charley. The later runs have a better initialization, but the discrepancy between the vortex as defined in the ICs and its actual intensity is still large. Because of this systematic problem, the fvGCM needs some spin-up time to actually build the hurricane vortex, which explains the somewhat erratic path of the developing systems in the first day, particularly evident in the run initialized at 0000 UTC 11 August. Moreover, Bonnie's development seems to be affected by the presence of a well-defined vortex for Charley in our model. The better-defined and deeper Charley appears to be in our integrations, the more to the east (and to observations) goes Bonnie's track. This suggests that Charley induces an eastward component of motion in Bonnie, in agreement with the known notion of two close hurricanes tending to rotate around a point somewhere between their centers, the weaker system displaying larger motion. However, in spite of the limitations derived from inadequate ICs, the tracks for Charley, once the vortex is built in the model, show a remarkably small dispersion, which indicates a substantial stability in the model's performance and its great potential.

4. Conclusions

In this work, preliminary results obtained with the high resolution finite-volume General Circulation Model developed at the NASA Goddard Space Flight Center are presented. Fifteen 5-day simulations involving four Atlantic tropical systems, chosen for their complex tracks, their dynamical differences, and their radically different life-cycles, are shown. The model, being run at the resolution of a quarter of a degree, has demonstrated the ability of capturing the development of all these very different systems, facing problems ranging from abrupt recurvature, intense extratropical transitions, multiple landfall with reintensification and interaction among vortices.

An important problem faced is represented by the initialization. Although a global set of initial conditions at a resolution of a quarter of a degree is very ambitious and perhaps will not be attainable in the near future, an

optimal use of satellite data, with selected data assimilation to improve the definition of the vortex at the initial stages, can compensate for the initialization deficiencies and bring further improvements to the performance of the fvGCM.

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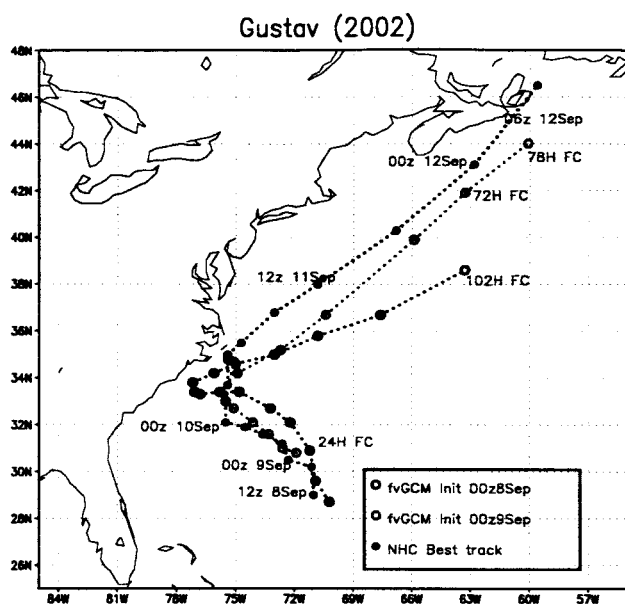


Figure 1. fvGCM simulations for hurricane Gustav compared with the observed track by the National Hurricane Center (NHC). Each dot represents the center position at 6-hour time increments.

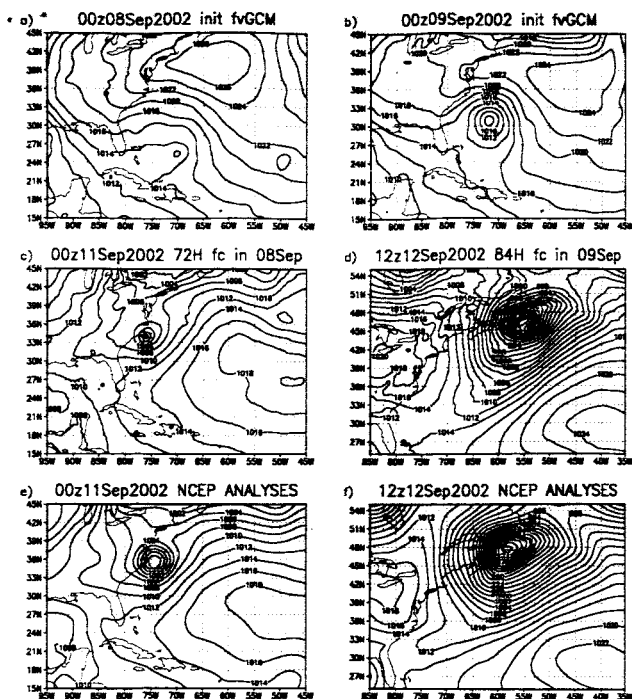


Figure 2. Sea level pressure (hpa). Panels above: fvGCM initialization over the area of interest for 0000 UTC 8 and 9 September. Central panels: 72 and 84 hour forecast initialized from 0000 UTC 8 and 9 September respectively. Panels below: corresponding NCEP validating analyses.

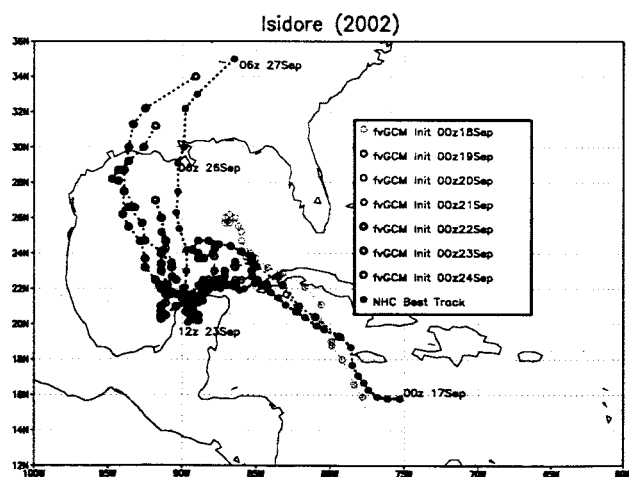


Figure 3. Same as Figure 1, but for hurricane Isidore.

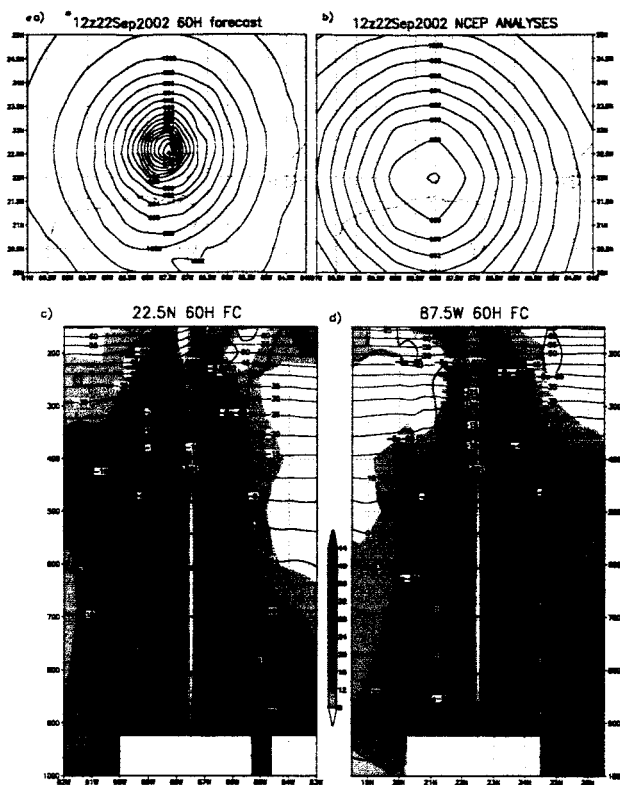


Figure 4. Above: sea level pressure (hPa) relative to 1200 UTC 22 September 2002. Top left: 60-hour forecast. Top right: NCEP validating analyses. Bottom panels: vertical cross-sections relative to the 60-hour fvGCM forecast. Plotted are wind speed (ms^{-1} , shaded), relative vorticity (s^{-1} , thick red/blue line), temperature ($^{\circ}C$, solid black line).

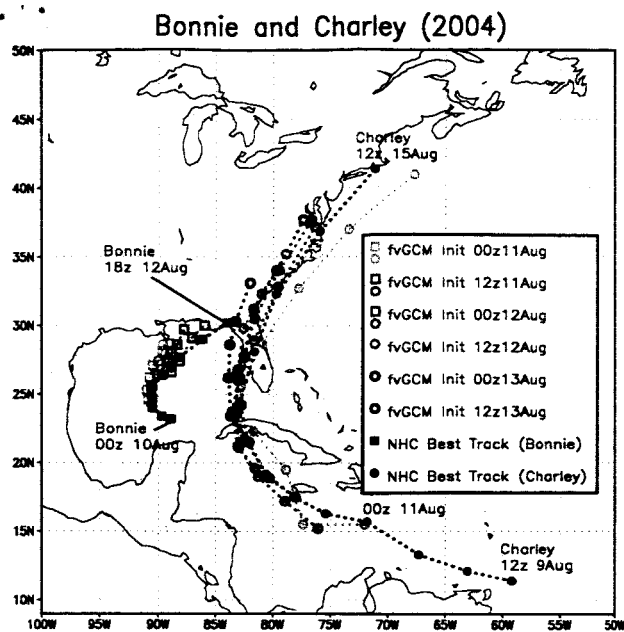


Figure 5. Same as Figure 1, but for Bonnie and Charley (2004). For clarity, positions are plotted at 6-hour and 12-hour time increments for Bonnie and Charley respectively.